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Simplifying a life cycle assessment of a mobile phone

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Abstract
Purpose The possibilities for full life cycle assessment (LCA) of new Information and Communication Technology (ICT) products are often limited, so simplification approaches are needed. The aim of this paper is to investigate possible simplifications in LCA of a mobile phone and to use the results to discuss the possibilities of LCA simplifications for ICT products in a broader sense. Another aim is to identify processes and data that are sensitive to different methodological choices and assumptions related to the environmental impacts of a mobile phone.
Methods Different approaches to a reference LCA of a mobile phone was tested: (1) excluding environmental impact categories, (2) excluding life cycle stages/processes, (3) using secondary process data from generic databases, (4) using input-output data and (5) using a simple linear relationship between mass and embodied emissions.
Results and discussion It was not possible to identify one or a few impact categories representative of all others. If several impact categories would be excluded, information would be lost. A precautionary approach of not excluding impact categories is therefore recommended since impacts from the different life cycle stages vary between impact categories. Regarding use of secondary data for an ICT product similar to that studied here, we recommend prioritising collection of primary (specific) data on energy use during production and use, key component data (primarily integrated circuits) and process-specific data regarding raw material acquisition of specific metals (e.g. gold) and air transport. If secondary data are used for important processes, the scaling is crucial. The use of input-output data can be a considerable simplification and is probably best used to avoid data gaps when more specific data are lacking.
Conclusions Further studies are needed to provide for simplified LCAs for ICT products. In particular, the end-of-life treatment stage need to be further addressed, as it could not be investigated here for all simplifications due to data gaps.

Keywords Information and communication technology (ICT) · Mobile phone, data · Simplification · Simplified LCA

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1 Introduction

Life cycle assessment (LCA) is resource-intensive methodology, and in practice, all LCAs include simplifications (Todd and Curran 1999). Different approaches or strategies for simplifying LCA have been developed (Christiansen et al 1997). A distinction can be made between qualitative (or semi-quantitative) simplified methods using checklists and matrices and quantitative-simplified methods (Hochschorner and

Finnveden 2003). The latter typically use easily available (or secondary) data instead of primary data from relevant sources because data collection is regarded as the most time-consuming task when conducting an LCA (Fleischer et al. 2001). Consequently, different approaches have been suggested and tested with the aim of simplification which can be defined as limiting data collection efforts, while keeping a relevant degree of robustness to make the results useful (c.f. Hunt et al. 1998).

During the recent decades, LCA has had a strong development (Guinée et al. 2011). Some of the development trends have had an influence on the possibilities of using simplified quantitative LCAs and are briefly described below.

Databases of process data are becoming increasingly comprehensive and available. A prominent example is the Ecoinvent database (Frischknecht et al. 2007a), but there are also other national and international initiatives (Finnveden et al. 2009). Through these databases, the context for performing LCAs has altered considerably with respect to availability of secondary data.

Input-output analysis (IOA) has been developed as another methodology for LCA (Lave et al. 1995; Hendrickson et al. 1997, 1998; Joshi 1999), but was initially devised as an economic tool for describing the whole economy in a society, including transactions between different sectors (Suh 2009). IOA becomes a viable tool for LCA practitioners when it includes information on average resource use and environmental emissions from each sector (Finnveden et al. 2009). It can then be used to estimate the environmental interventions generated throughout the upstream supply chain to deliver certain amounts of different goods and services. In this way, simplified LCAs can be calculated for product groups that correspond to the sectors. Since the data refer to product groups, they can only be regarded as estimates of specific products within the product group. However, it is argued that IOA data are more comprehensive than process-based LCA data since IOA covers the whole economy and is thus not dependent on the cutoffs used in conventional LCAs (Lenzen 2000). Hybrid methods combining the advantages of conventional LCA and IOA-based LCA may therefore be useful (Suh et al. 2004). Both IOA-based LCAs and hybrid methods have been used for calculating environmental impacts of ICT products (e.g. Williams 2004; Deng et al. 2011), and the usefulness of the approach has been discussed (Yao et al. 2010; Williams et al. 2011).

The focus on climate change in the society has led to increased use of carbon footprinting,[1] i.e. assessments considering only the global warming potential (GWP) (e.g. Finkbeiner 2009; Bala et al. 2010; Boguski 2010; Malmodin et al. 2010). The focus on one specific impact category can be seen as a simplification of LCA by reducing the data demand significantly, as data on CO_2 emissions are often more easily available and more reliable than other emissions data (Finnveden and Lindfors 1998).

Within the Information and Communication Technology (ICT) industry, the development and introduction of new products is currently rapid and wide-ranging. One example is that the number of electronic consumer goods and communication and media solutions of various kinds is steadily increasing (Eskelsen et al. 2009). The number of mobile phone users is also growing rapidly from 719 million subscriptions in 2000 to 2.2 billion in 2005 and an estimated 6.8 billion in 2013 (International Telecommunications Union 2013).

The widespread use of ICT products and the electronic distribution of services of different kinds represent use of energy and materials and also result in complex, potentially hazardous, waste management processes. In applying LCA to assess the life cycle impact of an increasing number of new and old products or to understand the main impacts of complex solutions, there is often a need for simplifications. Such simplified assessments involve, e.g. limiting the scope of the assessments depending on the target and focusing only on GWP and/or other selected environmental impact categories (e.g. Enroth 2009; Malmodin et al. 2010) using secondary process data from databases (e.g. Moberg et al. 2010) or excluding some life cycle stages. The effect of such simplifications on study results and on their interpretation and usage is not always well-known and explicitly addressed in the studies. Attempts have also been made to develop relationships between emissions of greenhouse gases and the mass of ICT products and their components (Teehan and Kandlikar 2013).

Although mobile phones are a significant part of the total carbon footprint of the ICT sector (Malmodin et al. 2010), the number of LCA studies in the scientific literature is limited (Arushanyan et al. 2014). Park et al. (2006) discuss results in the context of ecodesign, and Teehan and Kandlikar (2013) present results for greenhouse gases for products that are similar to mobile phones. Several mobile phone companies have also presented data for greenhouse gas emissions on the web, but without details about methods and system boundaries. This makes comparisons difficult since choices regarding methods, data and system boundaries can influence the results to a large extent (Santavaara and Paronen 2013).

The aim of this paper is to investigate possible simplifications in LCA of a mobile phone, evaluate their impact on the results and to discuss the possibilities of LCA simplifications for ICT products in a broader sense without losing significant amounts of information. Another aim is to present and analyse LCA results for mobile phones and to identify processes and data that are sensitive to different methodological choices and assumptions. The focus is on simplifications in the assessment, not in the presentation of results (i.e. making the results

[1] Carbon footprint is standardised by ISO (ISO 14067, Carbon footprint of products—requirements and guidelines for quantification and communication), which defines it in terms of life cycle impact related to GWP. It should be noted that for ICT products the GWP varies greatly with usage conditions, etc. Thus, a "carbon footprint" value only provides limited information regarding the GWP associated with an ICT product.

simpler for the reader to interpret). The overall objective was to use the results together with knowledge and experiences from other case studies (a) as a basis for formulating recommendations on how future LCA studies could, or should not, be simplified when assessing the environmental impacts of ICT products and services and (b) to discuss relevant indicators for ICT products, services and organisations.

2 Methods

2.1 The reference LCA

Simplifications can be investigated by either starting from scratch and carrying out an LCA with different types of methodological choices and comparing the results or by taking an existing reference LCA as the starting point, introducing different simplifications and comparing the results (Todd and Curran 1999). The latter approach was used in this study to test a set of possible simplifications and their effects on the outcome. A similar approach has been used by Lindfors et al. (1995) and Hochschorner and Finnveden (2003).

In this study, the effects of simplifications were compared against the results of a previous study (hereafter called the reference LCA) which assessed a mobile phone (a Sony Ericsson W890 including packaging and paper ware). However, in the reference LCA used here, phone accessories, i.e. charger, CD and USB cable, were not included. The reference LCA was based on Bergelin (2008), but incorporated a modified model for production of printed board assembly (PBA). The modifications of the PBA production model have limited influence on the overall production impacts compared to Bergelin (2008).

In Bergelin (2008), ISO 14040 and 14044 standards (ISO 2006a, b) were followed, and the GaBi 4.0 LCA software was used. This was also the case for the reference LCA, i.e. Bergelin (2008) with a modified PBA production model. The CML 2001 impact assessment method (Guinée et al. 2002) was used in the reference LCA, whereas an Ericsson internal impact assessment method was used in Bergelin (2008). The reference LCA was peer-reviewed by an independent review panel in 2010.

The data used by Bergelin (2008) and thereby in the reference study were obtained from Sony Ericsson using supplier resource and emission data to the greatest possible extent to get primary data in terms of representative averages of site-specific data for the production stage. Data were also taken from other relevant sources (such as PlasticsEurope and Boliden) and from the GaBi database (BUWAL and PE Gabi 4.0 data sets). These data to a large extent referred to material processing. Data on Sony Ericsson's in-house office activities such as yearly consumption of electricity, energy and paper and usage of computers and air travel by Sony Ericsson office employees were also included and allocated to the assessed product (Bergelin 2008). Data for gold production, a potentially important process, were collected from Peru and Sweden to provide a representative model of global gold production (Bergelin 2008). A large-scale site in Boliden, Sweden, represented high-technology mining of gold, and an average of two low-scale sites in Peru represented low-technology mining. One of the main differences between these data sets is that in small-scale mining in Peru, mercury is still used in the process. A global electricity mix made by Ericsson was used to model electricity use in production and global use of the mobile phone. However, for the Chinese production sites, a Chinese electricity mix was applied (Bergelin 2008).

Some less significant materials were assessed using proxy data based on materials with similar characteristics, e.g. data gaps on production of chromium were filled by data for nickel, while for platinum and palladium, gold production data were used (Bergelin 2008). Production of sub-components assumed to be of low importance was not included in the study. However, the materials in these components were included by scaling representative material data. In addition, transport of the main components to the final assembly site and transport of the mobile phone to the market were included. Average distribution distances and representative modes of transportation were used in the transport models (Bergelin 2008).

The end-of-life treatment stage was modelled as 50 % landfill, 25 % recycling in China and 25 % recycling in Sweden. This model was based on data from Boliden to give a rough estimate of a realistic scenario.

2.2 Testing possibilities for simplification

Information about the mobile phone studied and life cycle inventory results from the reference LCA were used as a basis for assessment of simplification possibilities. A set of approaches for simplification was tested through modifications of the data and models used in the reference LCA, and impacts on the results were evaluated. The various approaches for simplification tested were intended to form the basis for investigation of the following questions which can be seen as alternative strategies for simplification of quantitative assessments:

- Could impact categories be excluded or could a few act as representatives for all categories in this case study?
- Could some life cycle stages or processes be excluded, or could a few processes act as representatives for life cycle processes in this case study?
- To what extent would the use of secondary data instead of primary data affect the results and conclusions? Could secondary data be used without changing the overall conclusions?

As an evaluation rule for the case study, deviations from the results of the reference LCA of less than 10 % were considered an acceptable outcome of the simplifications made.

Environmental performance is related to many different types of impacts. The *first simplification approach* was therefore related to the covariance of these. If there are impact categories which give similar results regarding the importance of the different life cycle stages or processes, a simplification could possibly be to only study one of these. The covariance between the impact categories can be tested by investigating which are the most important life cycle stages and processes for different impact categories and whether some stages are non-significant and can be excluded. If the same stages or processes are the most or least important according to several impact categories, this is regarded as covariance between different impact categories. In the present study, 10 of the 11 environmental impact categories presented in CML 2001 (Guinée et al. 2002) were considered (radioactive radiation was not included in Bergelin (2008) or here), and the possibility to exclude some of them was appraised based on the reference LCA.

The *second simplification approach* examined the importance of different parts of the life cycle. There are many processes to consider in an ICT product system, covering all stages of the life cycle. Stages with a limited impact on the overall results of an LCA could perhaps be excluded or at least be handled in less detail, while processes which are of key importance for the environmental performance could be focused upon. The reference LCA was used and analysed regarding the possibility of focusing on some stages or processes.

The *third, fourth and fifth simplification approaches* looked into the use of secondary data which is often used when no primary data are available. Secondary data can be obtained from different sources, but here, we used process data from a generic LCA database (third approach), IOA data (fourth approach) and a simple linear model based on mass.

Looking further into the *third approach*, databases provide either generic average data or data reflecting specific conditions. Depending on the goal and scope of a study, the relevance of the different types of secondary process data may vary, e.g. if a study aims to provide information on average conditions, data reflecting specific conditions are less appropriate. To estimate the effects of using secondary process data, a simplified mobile phone model was built based on the reference LCA using the generic data sets from the Ecoinvent database version 2.2 (Frischknecht et al. 2007a), as provided by SimaPro 7.3.2 version (see Table 1). The aim was to build a simplified model that would use information and data that are considered to be easily accessible in order to test this approach for simplification. For some processes, no data set was available in the Ecoinvent database, and the process was therefore cut off. Processes not included in the simplified models were camera production, final assembly, test and warehousing, Sony Ericsson business activities, transport of raw materials and components and end-of-life treatment. The rationale for applying this cutoff when using secondary process data was that the corresponding processes are not easily modelled using only the product specification together with Ecoinvent data. Different approaches for using database data could be used and were tested in a stepwise way to better align it with the reference LCA, as described in Section 3.

In the *fourth simplification approach*, Swedish IOA data provided by Statistics Sweden (2010) were used. As described above, IOA provides data for product groups expressed as emission intensities, i.e. emissions per monetary unit. By multiplying emission intensity by the cost, emissions for the whole supply chain are calculated. Statistics Sweden provides two data sets of emissions intensities, one based on producer prices (i.e. prices excluding taxes and profits) and one based on consumer prices. These data represent only the cradle to store stages, so use and end-of-life treatment are not covered in this simplification. This study roughly assumed the producer price to be 1,000 SEK (corresponding to 110€ in August 2011) and the consumer price to be 2,500–3,000 SEK (corresponding to 270–320€ in August 2011). IOA data for 2006 were used in the assessment. The Swedish IOA data provided by Statistics Sweden include only a limited number of emissions. The focus here was only on CO_2 emissions, which probably comprise the majority of overall greenhouse gas (GHG) emissions in this case.

In the *fifth simplification approach*, the linear model between the mass of an ICT product and the embodied emissions of greenhouse gases developed by Teehan and Kandlikar (2013) is used. The model was developed as a regression model using data for 11 different ICT products suggesting that the greenhouse gas emissions from cradle to gate are 27 kg/kg (ibid.).

3 Results

The results of simplifications made by excluding impact categories, life cycle stages or processes in the assessment of the mobile phone are presented in Sections 3.1 and 3.2 and those simplifications made using secondary process data and models from Ecoinvent using IOA data using a regression model are presented in Sections 3.3 to 3.5.

3.1 Effects of excluding impact categories

In order to test the effects of excluding impact categories, the importance of different life cycle stages for different impact categories was tested. The relative contributions of the mobile phone's life cycle stages for all impact categories in the reference LCA are shown in Fig. 1. As can be seen from the diagram, the production stage was significant for all impact

Table 1 Mobile phone information provided by Sony Ericsson in accordance with the reference LCA used for the third simplification approach

Aggregated input data for the simplified model			Corresponding Ecoinvent process used for the third simplification approach
Components			
Main printed circuit board (PCB) area	13 cm^2		Printed wiring board, surface mount, lead-free surface, at plant/GLO U[a]
Other PCBs (total in phone) area	1.3 cm^2		Printed wiring board, surface mount, lead-free surface, at plant/GLO U[a]
Number of PCB layers (main board)	10		Not applicable
LCD unit area	16 cm^2		LCD module at plant/GLO U[a,b]
LCD weight	5 g		Same as previous
Main camera unit	1 unit		DATA GAP
Battery unit weight	19 g		Battery, LiIo, rechargeable, prismatic, at plant/GLO U[a]
Integrated circuits (IC) die area (total in phone)	2.9 cm^2		Integrated circuit, IC, logic type, at plant/GLO U[a] Integrated circuit, IC, memory type, at plant/GLO U[a]
IC weight	1.9 g		Same as previous
Gold weight (total in phone)	6.9 mg		Not specifically used in the model since it is part of the components data
Copper weight (total in phone)	2.8 g		Not specifically used in the model since it is part of the components data
Packaging and documentation	370 g		Paper, woodfree, uncoated, at regional storage/RER U[c]
Sony Ericsson activities			
Final assembly, test and warehousing	1 phone		DATA GAP
Sony Ericsson business activities	1 phone		DATA GAP
Total raw material and component transport			
Air	100 g	3,000 km	Partly included in raw material processes
Truck	600 g	1,500 km	Partly included in raw material processes
Transport to market			
Air	540 g[d]	7,600 km	Transport, aircraft, freight, intercontinental/RER U[e]
Truck	540 g[d]	3,400 km	Transport, lorry >32 t, EURO5/RER U[e]
Truck, estimation	540 g[d]	1,600 km	Transport, lorry >28 t, fleet average/CH U[e]
Use per year			
Daily full charging (use)	4.3 kWh	40 %	Electricity, low voltage, production UCTE, at grid/UCTE U[f]
Standby consumption (all the time)	0.9 kWh	50 %	Electricity, low voltage, production UCTE, at grid/UCTE U[f]
Total life time use (active use)	3.5 years		
End-of-life treatment	1 phone (50 % landfill, 50 % recycled)		DATA GAP

The full set of hardware data used was not published in Bergelin (2008)

[a] Hischier et al. (2007)

[b] When using Ecoinvent to develop the simplified models of the third simplification approach, the impact from the ICs in the LCD were counted twice, both as part of the LCD and as part of the total amount of ICs. With a simplification approach based on use of aggregated hardware data, this double counting effect could not be resolved. The impact of this double counting is not significant enough to impact the conclusions made

[c] Hischier (2007)

[d] Freight weight includes the mobile phone, packaging, instructions, CD, USB-cable and charger

[e] Spielmann et al. (2007)

[f] Frischknecht et al. (2007b)

categories, while the importance of the other life cycle stages varied. For example, transport (i.e. to the final assembly location and from there on to the sales location) was important (more than 20 %) for eutrophication, acidification and photochemical ozone creation, quite important (around 15 % of total impact) for abiotic depletion and GWP, but of limited importance for the other impact categories (Fig. 1).

A specific question is whether the results for GWP can be seen as representative for other impact categories too. In this particular case study, abiotic depletion was the only other

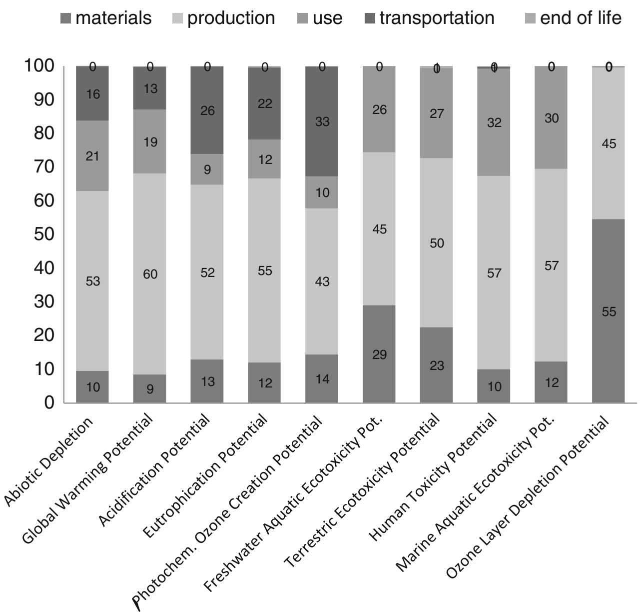

Fig. 1 Relative importance of environmental impacts for the life cycle of the mobile phone based on the reference LCA

impact category that followed the same pattern in terms of relative importance of the life cycle stages.

Groups of impact categories which showed a similar pattern of impacts were (1) abiotic depletion and GWP; (2) eutrophication, acidification and to some extent photochemical ozone creation; and (3) terrestrial and freshwater aquatic toxicity. However, it was not possible to identify one or a few impact categories that were representative of all the others. If several impact categories had been excluded, information would have been lost.

3.2 Effects of excluding life cycle stages or processes

As shown in Fig. 1 for the reference LCA, major environmental impacts were associated with the production stage, with between 43 % (photochemical ozone creation depletion) and 60 % (GWP) of all the various impacts occurring in this stage. The relative contribution from raw material acquisition, use and transportation varied between the environmental impact categories, with each contributing 10 % or more of the overall result for at least one impact category.

For the end-of-life treatment stage, the relative contribution of all impact categories was close to 0 % and, therefore, not visible in Fig. 1. The main reason for this was that positive impacts from avoided virgin production, resulting from the system expansion related to recycling and the assumed high degree of recycling, largely compensated for the negative impacts from waste management. In addition, the recycling process itself gave a low impact for the selected recycling scenario. Looking in more detail into the different life cycle stages in order to identify processes of high importance, i.e. processes that were not candidates for exclusion, some observations were made.

For *the production stage*, there were similar distribution patterns between life cycle processes for five of the 10 impact categories studied (Fig. 2), namely freshwater aquatic ecotoxicity, terrestrial ecotoxicity, GWP, marine aquatic ecotoxicity and human toxicity potentials. For all of these, the integrated circuits (ICs) had the greatest impact, followed by the LCD screen, and together, they contributed just over 70 % of the total impact of the production stage for each impact category.

For all impact categories, the ICs alone contributed 22–85 % of the total impact from the production stage, depending on impact category. The main source of impacts for all categories except ozone layer depletion was use of electricity. In terms of GWP in particular, half the impact related to IC production was due to electricity use and the other half to high GWP compounds (such as SF6 and PFCs) used in chip production. The toxicity impacts related to IC production were mainly due to use of electricity and not high GWP compounds. Thus, changes in electricity use and in SF_6 emissions related to IC production would affect GWP and toxicity differently.

In the raw *material acquisition stage*, some major contributors (e.g. gold, aluminium and steel production) were prominent in several impact categories (see Table 2). The environmental impact of the *use stage* was mainly due to electricity use for charging the mobile phone.

Transportation was a significant life cycle stage for five impact categories (photochemical ozone creation potential, acidification, eutrophication, abiotic depletion and GWP) (see Fig. 1). Air freight was the main source of these impacts, corresponding to around 80 % of the total impact potential from transport.

End-of-life treatment made a minor contribution to the total potential impact, and no processes of high significance were identified.

In the reference LCA, the use of electricity (including its supply chain impact) was a major contributor to the overall environmental impact potential of the mobile phone product. More specifically, it represented approximately 90 % of human and marine aquatic toxicity; 75 % of terrestrial and freshwater aquatic toxicity; more than 50 % of abiotic depletion and GWP; and 40 % of the acidification, eutrophication and photochemical ozone creation depletion impacts. Ozone layer depletion was not related to the use of electricity (Table 3).

In terms of the different life cycle stages (Table 3), electricity not only caused most of the environmental impact in the production stage but also made a major contribution in the use stage. Electricity generation caused less than 10 % of the impact for the raw material acquisition stage and less than 0.1 % for the transportation and end-of-life treatment

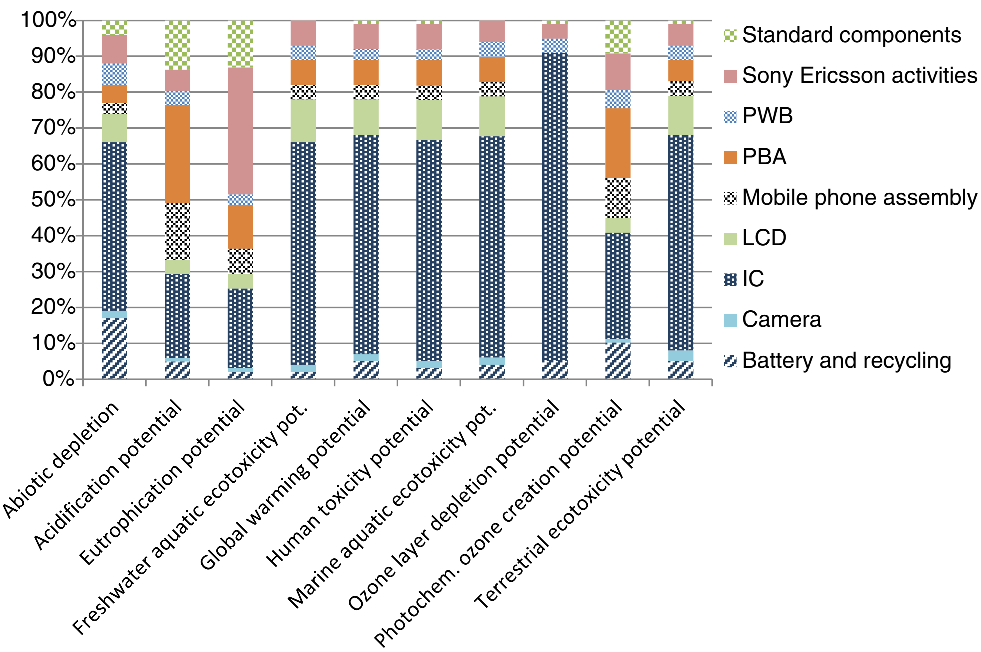

Fig. 2 Relative impacts of processes in the mobile phone production stage for the reference LCA

stage. Altogether, electricity generation was of major importance for the overall results and is a relevant indicator of environmental impact, but does not capture all impact categories.

3.3 Using secondary process data from LCA databases

The simplifications based on the use of secondary process data used the information provided in Table 1 for product and

Table 2 Description of resources and emissions from the mobile phone raw material acquisition stage, the processes that use the resources or generate the emissions and the relative contribution of this stage to the overall LCA results (based on Bergelin (2008) with life cycle impact assessment modified according to CML 2001)

Material acquisition			
	Resources and emissions with the greatest relative contribution in the material stage	Process with major contribution	Overall contribution of the material stage to this impact category (%)
Abiotic depletion	Hard coal (37 %) and crude oil (28 %).	Electricity generation. Aluminium, packaging, stainless steel and polycarbons also have impacts	10
Acidification potential	Nitrogen oxides (37 %), sulphur dioxide (37 %) and nitrogen dioxide (9 %).	Gold production (~26 %), also plastics and aluminium	13
Eutrophication potential	Nitrogen oxide (58 %).	Gold production (~30 %)	12
Freshwater aquatic ecotoxicity pot.	Copper (81 %).	Gold production (~81 %)	29
Global warming potential	Carbon dioxide (86 %).	Electricity generation, polycarbons, aluminium, waste, etc.	9
Human toxicity potential	Selenium (38 %), arsenic (20 %), nickel (13 %).	Nickel (~16 %) and gold (~14 %) production	10
Marine aquatic ecotoxicity potential	Hydrogen fluoride (29 %), selenium (21 %) and copper (19 %).	Aluminium production, electricity generation and gold production	12
Ozone layer depletion potential	Halogenated organic emissions (Halon 1301) (91 %)	Aluminium production (~66 %) and corrugated cardboard (~17 %).	55
Photochem. ozone creation potential	NMVOC (28 %), sulphur dioxide (20 %) and nitrogen oxides (20 %)	Aluminium (~17 %) and other "polyproducts" (~31 %)	14
Radioactive radiation	Carbon14 (65 %) and caesium137 (25 %)	Steel production (~56 %) and copper (~10 %)	47
Terrestrial ecotoxicity potential	Mercury (77 %)	Gold production (~65 %)	23

Table 3 Contribution [percent] of electricity generation to the impact categories within different life cycle stages of the mobile phone (based on Bergelin 2008)

	Raw material acquisition	Production	Use	End-of- life treatment	Transportation	Total contribution
Abiotic depletion	4	37	21	−0.02	0.03	61
Acidification potential	2	34	9	−0.01	0.01	45
Eutrophication potential	2	24	9	−0.01	0.02	35
Freshwater aquatic ecotoxicity pot.	4	44	26	−0.02	0.04	74
Global warming potential	3	34	18	−0.02	0.03	55
Human toxicity potential	6	55	32	−0.03	0.05	93
Marine aquatic ecotoxicity pot.	5	53	30	−0.03	0.05	89
Ozone layer depletion potential	0	0	0	0	0	0
Photochem. ozone creation potential	2	26	9	−0.01	0.01	36
Radioactive radiation	0	0	0	0	0	0
Terrestrial ecotoxicity potential	5	46	26	−0.02	0.04	77

scenario data and data sets (models and data) available in Ecoinvent 2.2. In order to achieve alignment with the reference LCA, the data were modified in three steps referred to as simplified models I, II and III, respectively:

- Simplified model I: Aggregation of applicable Ecoinvent data and models in accordance with Table 1, with an LCD screen model scaled based on area.
- Simplified model II: Model based on simplified model I, but with the LCD screen scaled based on weight.
- Simplified model III: Model based on simplified model II, but with gold and copper weight adjusted to match the amounts used in the reference LCA.

The different parameters of all simplified models are presented in Table 4, and the results for the reference LCA and simplified models I and II in Table 5.

Simplified model I gave lower results than the reference LCA for abiotic depletion, global warming and photochemical ozone creation, but higher impacts, in some case significantly higher, for the other categories (Table 5). This shows that there are significant differences between simplified model I and the reference LCA, and that similarities in GWP results are not necessarily accompanied by similarities in results for other impact categories.

Secondary process data from LCA databases are not always provided in a form that makes them directly applicable. In simplified model I, the Ecoinvent LCD screen model was used, but adjusted by scaling the available data set for a 17″ LCD screen down to the applicable area shown in Table 1. The IC data were scaled by area. However, this scaling produced unreasonable results, basing it on screen size led to a weight of 133 g LCD screen per mobile phone, compared with the actual 5 g in the reference LCA. For IC circuits, the weight

Table 4 Hardware data used in simplified models I–III

	HW data according to Table 1	Simplified model I (EcoInvent)	Simplified model II (EcoInvent)	Simplified model III (EcoInvent)
LCD area	16 cm^2	16 cm^2	(0.6 cm^2)	(0.6 cm^2)
LCD weight	5 g	(133 g)	*5 g*	5 g
Gold weight[a]	6.9 mg	(29 mg)	(9 mg)	*6.9 mg*
Copper weight	2.8 g	(22 mg)	(12.3 g)	*2.8 g*
IC weight	1.9 g	1.2 g logic IC + 0.51 g memory IC	*1.9 g*	1.9 g
IC die area	2.9 cm^2	7.3 cm^2 logic IC + 2.8 cm^2 memory IC	(2.0 cm^2 logic IC + 1.7 cm^2 memory IC)	(2.0 cm^2 logic IC + 1.7 cm^2 memory IC)
PCB area	14.4 cm^2	(24 cm^2)	(24 cm^2)	(24 cm^2)
PCB layers	10	(6)	(6)	(6)

Numbers in brackets are provided for comparison and were not used as input data, but were a consequence of the data used. Figures in italics represent changes in input data compared with the previous simplified model

[a] Amount of 99 % virgin gold used in the LCA model

Table 5 Environmental impact indicator results for the reference LCA, simplified model I and simplified model II

Impact category	Reference LCA	Simplified model I	Simplified model II
Abiotic depletion [g Sb eq]	137	126	80
Acidification [g SO2 eq]	54	97	53
Eutrophication [g PO4—eq]	8.7	84	41
Global warming (GWP100) [kg CO2 eq]	22	19	12
Ozone layer depletion [10*mg CFC-11 eq]	1.3	15	11
Human toxicity [kg 1,4-DB eq]	3.5	29	15
Freshwater aquatic ecotoxicity [kg 1,4-DB eq]	1.1	14	7,6
Marine aquatic ecotoxicity [ton 1,4-DB eq]	2.2	36	19
Terrestrial ecotoxicity [10*g 1,4-DB eq]	5.0	15	10
Photochemical oxidation [g C2H4]	4.5	4.0	2.2

produced by scaling was slightly lower (1.7 g per mobile phone instead of 1.9 g). The IC circuits in simplified model I gave a very low GWP impact per area compared with those in the reference LCA model. This is not visible in the total GWP results for simplified model I, which had a slightly lower total GWP value than the reference LCA model, mainly due to the high impact from the too high LCD weight.

Simplified model II, where the actual weights of the LCD module and the ICs in the mobile phone were used as input parameters for the scaling of the Ecoinvent models, was therefore introduced. This resulted in less difference with the reference LCA than simplified model I for impact categories other than GWP, abiotic depletion and photochemical ozone creation (Table 5). However, despite the many data gaps in the simplifications used (see Abstract), simplified model II still gave a higher environmental impact per mobile phone for these impact categories than the reference LCA. In contrast, for GWP, abiotic depletion and photochemical ozone creation, simplified model II gave a considerably lower impact than the reference LCA. For GWP, this was mainly due to the Ecoinvent model having considerably lower values for electricity use in its IC and LCD production processes. The low wafer area per mass of IC also reduced the GWP level.

With simplified models I and II, it was found that the printed circuit boards (PCBs) had a considerably greater impact on ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity and marine aquatic ecotoxicity compared with in the reference LCA, but this was not studied further. Note, however, that PCB weight was about three times higher in the simplified models, as it was scaled based on surface area and number of layers but not according to weight.

The high values for the toxicity indicators with simplified models I and II compared with the reference LCA were largely dependent on the unreasonably high amounts of virgin gold and copper resulting from the first and second round of model simplifications. Therefore, in simplified model III, the amounts of gold and copper were adjusted to better match the material usage of the mobile phone in the reference LCA, as estimated from the material content. Simplified model III resulted in about 30 % less human toxicity, 30 % less fresh water aquatic ecotoxicity, 35 % less marine aquatic ecotoxicity and 10 % less terrestrial ecotoxicity compared with simplified model II (Table 6). However, the results were still considerably higher than the corresponding results from the reference LCA.

Waste from the material acquisition stage, more specifically the sulphidic mining tailings from gold, copper and lignite extraction, dominated all toxicity impact indicators in simplified model III, but to a lesser extent than in simplified models I and II. However, it was still the main reason for the large differences between simplified models I–III and the reference LCA. Lignite mining tailings also became relatively more significant as the mass of gold and copper were reduced in simplified model III. A significant difference between the reference LCA and the simplified models using Ecoinvent data concerned the time perspective for emissions from landfilled materials. In the Ecoinvent data, emissions are covered with a long-time perspective (60,000 years), whereas the reference LCA used a shorter time perspective. Since emissions from landfilled materials are slow processes, this difference will significantly influence the total emissions of potential toxic metals.

The GWP impacts decreased with the changes implemented in simplified models I–III (Fig. 3). The differences were mainly due to the die area being too small and the electricity use for the die processes too low when scaling by weight. To achieve more realistic GWP values, the effect of scaling the IC model by die area could be tested. However, such adjustment would demand considerable previous knowledge and skills in the field of electronics, and the assessment would therefore not be very simple, i.e. the simplification potential of the approach would be limited. As the differences between the reference LCA and the simplified models were still considerable after this third iteration, no further tests were made, and simplified model III was not analysed for additional impact categories.

Table 6 Environmental impact indicator results for the four CML 2001 toxicity impact indicators for the reference LCA and simplified models II and III

Impact category	Reference LCA	Simplified model I	Simplified model II	Simplified model III
Human toxicity [kg 1,4-DB eq]	3.5	29	15	10
Freshwater aquatic ecotoxicity [kg 1,4-DB eq]	1.1	14	7.6	5.3
Marine aquatic ecotoxicity [ton 1,4-DB eq]	2.2	36	19	12
Terrestrial ecotoxicity [10*g 1,4-DB eq]	5.0	15	10	9.1

3.4 Using IOA data

The estimated consumer price of 2,500–3,000 SEK resulted in estimated emissions of 27.5–33 kg CO_2 per mobile phone using Swedish IOA data for telecommunications equipment provided by Statistics Sweden (2010). Assuming a producer price of 1,000 SEK and using environmental account data for electric and telecommunications products resulted in a value of 16 kg CO_2e per mobile phone.

The full life cycle emissions per mobile phone according to the reference LCA were 22.4 kg CO_2e. However, as the data in the Swedish environmental accounts only reflect the emissions from cradle to store (i.e. no use or disposal), the IOA results should instead be compared to a value of 18 kg CO_2e.

3.5 Using a linear model

The weight of the phone is 79 g, the charger 57 g and the USB cable 39 g (Bergelin 2008). If these are added and used in the simplified model in Teehan and Kandlikar (2013), the result is 4.7 kg CO_2 equivalents excluding the use phase. This is significantly lower than the 18-kg CO_2 it can be compared to, although the charger and the USB cable are not included in the reference LCA. This confirms that the model underestimates the emissions from light-weight products as suggested by Teehan and Kandlikar (2013).

4 Discussion

For most ICT products, the life cycle inventory phase of an LCA can be very extensive and time-consuming since there are many different electronic components and materials in a product. With continuous development of new models, the possibility to perform complete LCAs for all products is limited. The impacts from ICT products may change considerably as technologies develop and user practices change, and the latter can change rapidly. Thus, the results of comprehensive assessments may not be of lasting relevance and methods to perform simplified assessments would be useful. On the other hand, changes in technology and user practices may lead to trend shifts in the most important life cycle processes, so the accuracy of simplification in a particular case needs to be carefully considered. It should also be kept in mind that simplifications may lead to less accurate results.

Depending on the goal and scope of an environmental assessment, the possibilities for simplification may vary. For example, the aim of an LCA may be to learn more about the product, identify hotspots, compare suppliers or compare products. In all these cases, lack of relevant data may be a problem and if approximations and estimations have to be made, an overall simplification at an early stage *may* provide just as good decision support. Bala et al. (2010, p. 496) point out that simplified approaches may facilitate increased use of life cycle thinking and LCA "while still producing scientifically sound and robust results". In testing simplified approaches for the assessment of GHG emissions, those authors obtained results in line with more complete studies. However, they did not consider other impact categories.

In this study, we tested a number of simplifications and compared the results against those of a reference LCA. All LCAs are model-based and therefore to some extent represent simplifications compared with the real situation. Thus, the assumption that agreement with the reference LCA represents *correct* results per se can be criticised, especially if some of the secondary data use other methodological choices or more comprehensive lists of emissions. However, comparisons with the results of the reference LCA are of interest in order to better understand the consequences of different choices. The choice of appropriate ways of simplification can also depend on the intended use of the assessment. If the intention is to identify hot spots and critical issues for further study comprehensiveness is most important since if an aspect is not

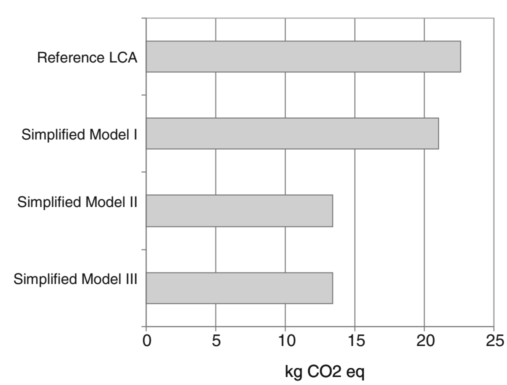

Fig. 3 Global warming results for the different mobile phone LCA simplification models tested in the third approach

included, it cannot be identified as a hot spot. Precision in the data may on the other hand be less relevant. In such cases, the use of secondary data can be useful. If the intended use is to choose between products or suppliers, generic data for product groups for example from input-output bases assessment may be less useful since different products within the product group cannot be distinguished. On the other hand, impact categories or life cycle stages that previous studies have indicated are of less importance can be given less attention.

4.1 Excluding impact categories (approach 1)

Regarding the use of one impact category as an indicator of others for the mobile phone product assessed here, such a simplification may be an option for GWP and abiotic depletion. However, acidification and eutrophication, which are also often related to energy use, did not have the same distribution between life cycle stages as GWP and abiotic depletion in this study. The toxicological impact categories also showed a different pattern than GWP and abiotic depletion. Other studies have also reported limited covariance between results for GWP and toxicological impacts (Laurent et al. 2012). The different toxicological impact categories showed similar patterns to each other in some cases, e.g. with respect to the distribution of impacts between the different processes within the production stage. However, the sources of impact differed in some cases, and thus, co-variations may not be systematic. In addition, the benefits of excluding, e.g. one or two toxicological impact categories may be limited, as this would scarcely lead to substantially reduced inventory efforts. In general, it would be interesting to repeat this study for other products to see whether the co-variations between impact categories observed here were repeated.

The co-variation between GWP and abiotic depletion may also be the result of the characterisation method chosen for resource depletion. There are several methods available, and they produce different results (Finnveden et al. 2009). The CML 2001 method used here typically imparts higher importance to fossil fuels than other methods (Finnveden 2012), and higher covariance can thus be expected than for some other methods.

Many LCA studies focus only on one or a few impact categories. However, as long as no claims are made regarding one impact category based on the results of another or regarding general environmental performance, this is not seen as a simplification, but rather as a limitation in scope. In the present case study, only considering GWP impact as input for decisions might have led to unwanted consequences for other impact categories, which might well have a different impact distribution between life cycle stages and processes. Thus, such limitations in scope could lead to inaccurate conclusions.

4.2 Excluding or focusing on specific life cycle stages/processes (approach 2)

The production and use stages are often of great importance in the life cycle of ICT products (Park et al. 2006; Arushanyan et al. 2014); this is also shown in this study. The end-of-life treatment stage had a rather limited impact here, although there are large uncertainties about waste treatment and possible data gaps. Many studies have been made of e-waste management and environmental impacts (Hischier et al. 2005; Barba-Gutiérrez et al. 2008; Robinson 2009; Duan et al. 2009; Chancerol et al. 2009; Umair et al. 2013). Therefore, at this stage, we would not recommend excluding the end-of-life stage from LCAs of ICT products. The transportation and the raw material acquisition stages represented more than 10 % of the total impact for some impact categories and should thus not be neglected.

While the basic life cycle stages should not be neglected, it may still be possible to exclude insignificant individual processes within a life cycle stage while considering both their individual and accumulated impact, as well as the effect on the overall accuracy of results. This demands further studies.

4.3 Using secondary process data (approach 3)

Trying to use easily available data from the Ecoinvent database, several processes were found not to be covered and therefore processes were cut off (see Abstract for details). This could be one reason why the impact potentials for abiotic depletion, global warming and photochemical oxidation were lower in simplified models I–III than in the reference study. However, for most impact categories, the simplified models gave higher results than the reference LCA in spite of the cutoffs. For toxicity, particularly, one reason for this could be that the Ecoinvent data have broader system boundaries concerning time, e.g. for landfill processes. The reference LCA used a cutoff where long-term emissions were excluded, which is of particular relevance for toxicological impacts as further discussed below. Another reason can be that the list of emissions is more comprehensive in some secondary data sources. This also illustrates that the choice of secondary easily accessible data is not only a choice of data source but also of models and system boundaries. Easily accessible data from databases (or from input-output data further discussed below) can therefore be more complete in some senses while being less specific and therefore less relevant for some applications. It is therefore not always clear which data are preferable.

Use of secondary process data from an LCA database showed that the information used as model input is highly important. If simplified models are created, the product and process information on which the assessment is based must be chosen with care, especially if performed by non-experts in

the field of electronics and components. As general data sets in a database probably do not cover the exact size and type of the specific component being modelled, they often need to be scaled up or down. This study demonstrated that such scaling is crucial and basing it on area or weight can greatly affect the overall results of the assessment. In order to facilitate the use of generic component data in databases, they could be structured so that models could be categorised as processes which are scaled by area (e.g. LCD, IC and PCB) and processes which are scaled by weight (e.g. materials). Comparative studies on other ICT products have shown that data for ICs and PCBs are highly uncertain and variable and requires further attention (Teehan and Kandlikar 2012). It has also changed with time and technology (Boyd et al 2010). It is therefore not surprising that the change of data source can lead to a change in result

Although the environmental impact of the raw material acquisition stage was rather low (Fig. 1) for several of the impact categories, gold production had a major influence on the total impact. Furthermore, when using Ecoinvent data to test the effect of using secondary process data, the results indicated that gold production could have a much larger impact than suggested in the reference LCA and also that related impact categories (mainly toxicity) may be more substantial than indicated there. For toxicity, the reason for the variation was a difference in modelling leakage from mining tailings dumps (a major contributor to all toxicity impact potentials and to eutrophication in simplified models I–III) and the choice of time boundaries for emissions. Ecoinvent covered a time span of 60,000 years for landfill (Doka 2009), while the reference LCA focused on the short-term (100 years) impact. Since emissions from landfill can continue for very long periods, this difference can be significant. It seems reasonable to assume that both perspectives are relevant and complement each other (Finnveden et al. 1995).

In addition to the difference in time perspective, there were also differences in the mine models used. Ecoinvent uses a more conservative model from a UN study (Classen et al. 2009, Part XIV:17), while the reference LCA used data from Boliden and data from a small-scale Peruvian gold mine in order to reflect a realistic scenario. The differences in results highlight the risk of the raw material acquisition stage being viewed as more or less important depending on the data used for this stage. In this case study, use of different types of data and models generally affected the results. This is an area where further research is needed to create an understanding of the consequences of different choices.

4.4 Using IOA data (approach 4)

Using Swedish IOA, data can in principle be a very significant simplification since data on emission intensities are available online, and all that is needed is data on product price. Thus, results can be obtained very quickly. Here, the IOA data resulted in estimated GHG emissions values of 16–33 kg CO_2e depending on assumptions compared with 18 kg CO_2e estimated by the reference LCA to represent cradle-to-gate emissions. This is line with previous studies that have indicated that results from IOA-based LCAs of production of ICT products are higher than results from process-based LCAs (Williams 2004; Deng et al. 2011). This is because IOA data are more comprehensive than process-based LCA data since the whole economy is included in the IOA (Suh et al 2004). In contrast, process-based LCAs always have to include cutoffs and truncation errors (Lenzen 2000; Majeau-Bettez et al. 2011). On the other hand, IOA data are average data for a product group, and thus, significant uncertainties can be expected, while price variations may reflect differences in popularity between different brands rather than differences in physical characteristics and production processes. The best use of IOA data may be as secondary data when more precise data are not available to avoid having data gaps (Suh and Huppes 2002). The results presented here suggest that IOA data could be useful if mobile phones are a minor part of a study. If mobile phones are the focus of the study, the online version of the Swedish IOA data used here are not so useful since it only provides an answer without further possibilities to analyse the results, identify hot spots or test changes.

4.5 Finding hotspots/indicators of environmental performance

Considering all life cycle stages of the mobile phone in the case study, electricity generation was a recurring process and was associated with major impacts of different kinds. For the toxicological impact categories, GWP and abiotic depletion, electricity was the main contributor to the overall environmental impact of the reference LCA, especially in the production and use stages. Focusing the primary data collection process on some specific processes, including electricity generation, could be a relevant means of simplification. In terms of the raw material acquisition, production and use stages, some other processes were identified as major contributors to the environmental impacts in the case study. For example, in addition to electricity consumption during production and use, raw material acquisition of specific metals (e.g. gold), air transport and key component data, primarily for ICs, were important processes. Thus, it could potentially be appropriate to simplify studies on similar products by focusing the main data collection efforts on these processes, while accepting lower data quality for other processes. Note also that key processes vary between impact categories, e.g. for ozone layer depletion other processes are more important.

Many ICT products use the same basic components and could potentially have similar environmental impact profiles, so some of the results obtained here may be generally applicable. However, similarities in basic components do not

necessarily mean similarity in overall design, e.g. characteristics such as energy consumption may differ between similar products. It can be noted that some major differences exist between products and product generations. One example is product size, which can affect the relative importance of the production and use stages. Other examples are lifetime, product mobility and use of power-saving features. Thus, a simplification may not necessarily have similar implications for different ICT products. For many products, there are even considerable differences within product type depending on configuration, use profile, etc.

The age of the data is important when suggestions for simplifications are made based on previous LCA studies, as ICT products are changing rapidly. Components are gradually being improved and new components and products developed, while user practices are also changing rapidly. This means that the environmental performance profile may change quickly, and that simplifications that are reasonable at one point in time may not be relevant in a long-term perspective.

An illustration of how the relative importance of different aspects may change with time is the Key Environmental Performances Indicators (KEPIs) developed based on LCA results (Singhal 2005). The intended application was in designing new products. For mobile phones, indicators were suggested for production (including raw material acquisition), transportation and use. However, some of the impacts identified in the KEPIs have now largely been addressed by mobile phone producers, i.e. the standby consumption of chargers and solder paste lead, emphasising that such indicators need to be regularly updated as problems are resolved or shifted. The KEPIs cited above did not address all important processes identified in this case study, e.g. precious metals (specifically gold), and did not focus on the possibility of more energy-efficient production processes, but rather on the different types of materials used.

5 Conclusions

This study assessed five approaches to simplify LCA for a mobile phone: (1) excluding environmental impact categories, (2) excluding life cycle stages/processes, (3) using secondary process data from a commercial LCA database, (4) using economic input-output data from national environmental accounts and (5) using a linear model. Simplifications relating to end-of-life treatment of the mobile phone were not assessed.

This study indicates that it is not possible to identify one or a few impact categories which were representative of all others. When some impact categories were excluded, significant information was lost. The GWP indicator could not be used as an indicator for, e.g. toxicity impact categories, although most processes/activities identified as being of high importance for GWP are also important for toxicity. This was because the toxicity impacts emerging from raw material extraction affected the toxicity categories more than GWP, although the dominant toxicity impact from fuel incineration covaried with GWP.

The results showed that life cycle stages related to raw material acquisition, production, use and transport should be taken into account. The production stage contributed approximately 40–60 % of the total impact potential for the different impact categories assessed. Raw material acquisition and product use made a contribution of approximately 10 % or more, while transport also contributed more than 10 % to half the impact categories studied. The end-of-life treatment stage gave very low contributions to the overall results, mainly due to the positive contribution from recycling, but due to major uncertainties related to this (future) life cycle stage, it was not seen as candidate for exclusion. In general, a precautionary approach seems relevant when excluding life cycle stages from LCA, as their contribution to the total impact varies between impact categories.

To conduct a simplified environmental assessment of an ICT product similar to the mobile phone assessed here, the suggestion based on this study is to focus main data collection efforts on specific data for energy use during production and use, raw material acquisition of specific metals (e.g. gold), air transport and key component data, primarily for ICs. Less detailed and less specific data could potentially be used for other processes. However, if secondary data are used for important production processes and raw materials, scaling is crucial and can affect the LCA results. Production processes and materials should be separated, and the scaling of production processes should be based on area (e.g. for IC, LCD and PCB) and the scaling of raw materials on weight. Even then, scaling must be performed with great caution as it can result in disproportionate changes in different inventory data and impact potentials. The IC and LCD models from the Ecoinvent 2.2 database that were used in this study were not fully representative of the components of the mobile phone assessed.

The impact categories related to toxicity varied widely depending on input data and impact modelling. The toxicity impacts in the simplified models developed in the study originated mainly from coal mining waste and coal incineration and from long-term emissions from mining waste related to extraction of rare/valuable metals (gold, copper, etc.). These results differed considerably compared with the reference LCA, mainly due to the time perspective and mining scenarios applied. There may also be data gaps for toxic emissions from the production stage, as these parameters are often not monitored. Due to the high uncertainty related to the toxicity impact categories, the results of the related simplifications cannot be fully interpreted, but, e.g. the time perspective applied had a considerable effect on the overall results.

The use of IOA data can be a considerable simplification, but the results showed variations depending on the assumptions made and the Swedish IOA data used included only a limited number of emissions. IOA data are probably best used when more specific data are not available to avoid data gaps. Further studies are needed to simplify LCA for ICT products in particular the end-of-life treatment stage needs to be addressed in more detail.

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References

Arushanyan Y, Ekener Petersen E, Finnveden G (2014) Lessons learned—review of LCAs for ICT products and services. Comput Ind 65:211–234

Bala A, Raugei M, Benveniste G, Gazulla C, Fullana-i-Palmer P (2010) Simplified tools for global warming potential evaluation: when 'good enough' is best. Int J Life Cycle Assess 15:489–498

Barba-Gutiérrez Y, Adenso-Diaz B, Hopp M (2008) An analysis of some environmental consequences of European electrical and electronic waste regulation. Resour Conserv Recycl 52:481–495

Bergelin F (2008) Life cycle assessment of a mobile phone—a model on manufacturing, using and recycling. Master thesis. Uppsala University, Uppsala

Boguski TK (2010) Life cycle carbon footprint of the National Geographic magazine. Int J Life Cycle Assess 15(7):635–643

Boyd SB, Horvath A, Dornfeld DA (2010) Life-cycle assessment of computational logic produced from 1995 through 2010. Environ Res Lett 5:014011. doi:10.1088/1748-9326/5/1/014011

Chancerol P, Meskers CEM, Hagelüken C, Rotter VS (2009) Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. J Ind Ecol 13:791–810

Christiansen K, de Beaufort-Langeved A, van den Berg N, Haydock R, ten Houten M, Kotaji S, Oerlemans E, Schmidt W-P, Stranddorf HK, Weidenhaupt A, White PR (1997) Simplifying: just a cut? SETAC Europe LCA, Brussels

Classen M, Althaus H-J, Blaser S, Tuchschmid M, Jungbluth N, Doka G, Faist Emmenegger M, Scharnhorts W (2009) Life cycle inventories of metals. Final report Ecoinvent data v2.1, no. 10. EMPA, Swiss Centre for Life Cycle Inventories, Dübendorf

Deng L, Babbitt CW, Williams ED (2011) Economic-balance hybrid LCA extended with uncertainty analysis: case study of a lap-top computer. J Clean Prod 19:1198–1206

Doka G (2009) Life Cycle Inventories of Waste Treatment Services. Ecoinvent report no. 13. Swiss Centre for Life Cycle Inventories, Dübendorf

Duan H, Eugster M, Hischier R, Streciher-Porte M, Li J (2009) Life cycle assessment study of a Chinese desktop personal computer. Sci Total Environ 407:1755–1764

Enroth M (2009) Environmental impact of printed and electronic teaching aids, a screening study focusing on fossil carbon dioxide emission. In Advances in printing science and technology, Proceedings of the 36th International Research Conference of iarigai, Vol. 36. IARIGAI, Darmstadt

Eskelsen G, Marcus A, Feeree WK (2009) The digital economy fact book, 10th edn. Progress and Freedom Foundation, Washington

Finkbeiner M (2009) Carbon footprinting—opportunities and threats. Int J Life Cycle Assess 14:91–94

Finnveden G (2012) Exergy as a measure of resource use in LCA and other sustainability assessment methods. In: Proceedings of the 4th International Conference on Waste and Biomass Valorisation. September 10–13, Porto

Finnveden G, Lindfors L-G (1998) Data quality of life cycle inventory data—rules of thumb. Letter to the editor. Int J Life Cycle Assess 3: 65–66

Finnveden G, Albertsson AC, Berendson J, Eriksson E, Höglund LO, Karlsson S, Sundqvist J-O (1995) Solid waste treatment within the framework of life-cycle assessment. J Clean Prod 3:189–199

Finnveden G, Hauschild M, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in life cycle assessment. J Environ Manag 91:1–21

Fleischer G, Gerner K, Kunst H, Lichtenvort K, Rebitzer G (2001) A semi-quantitative method for the impact assessment of emissions within a simplified life cycle assessment. Int J Life Cycle Assess 6(3):149–156

Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M, Wernert G (2007a) Overview and Methodology. Ecoinvent report no. 1. Swiss Centre for Life Cycle Inventories, Dübendorf

Frischknecht R, Tuchschmid M, Faist Emmeneger M, Bauer C, Dones R (2007b) Strommix und Stromnetz. In: Dones R (ed) Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystement und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Ecoinvent report no. 6, v2.0. Paul Scherrer Institut Villingen, Swiss Centre for Life Cycle Inventories, Dübendorf

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Wegener Sleeswijk A, Suh S, Udo de Haes HA, de Bruijn JA, van Duin R, Huijbregts MAJ (2002) Handbook on life cycle assessment: operational guide to the ISO Standards. Series: eco-efficiency in industry and science. Kluwer, Dordrecht

Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, Ekvall T, Rydberg T (2011) Life cycle assessment: past, present and future. Environ Sci Technol 45:90–96

Hendrickson CT, Horvath A, Joshi S, Klausner M, Lave LB, McMichael FC (1997) Comparing two life cycle assessment approaches: a process model- vs. economic input-output-based assessment. IEEE Int Symp Electron Environ 176–181

Hendrickson C, Horvath A, Joshi S, Lave L (1998) Economic input–output models for environmental life-cycle assessment. Environ Sci Technol 32:184A–191A

Hischier R (2007) Life cycle inventories of packagings and graphical papers. Ecoinvent report no. 11. Swiss Centre for Life Cycle Inventories, Dübendorf

Hischier R, Wäger P, Gauglhofer J (2005) Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling system for waste electrical and electronic equipment (WEEE). Environ Impact Assess Rev 25:525–539

Hischier R, Classen M, Lehmann M, Scharnhorst W (2007) Life cycle inventories of electric and electronic equipment: production, use and disposal. Ecoinvent report no. 18. Empa/Technology & Society Lab, Swiss Centre for Life Cycle Inventories, Dübendorf

Hochschorner E, Finnveden G (2003) Evaluation of two simplified life cycle assessment methods. Int J Life Cycle Assess 8:119–128

Hunt RG, Boguski TK, Weitz K, Sharma A (1998) Case studies examining LCA streamlining techniques. Int J Life Cycle Assess 3(1):36–42

International Telecommunications Union (2013). The World in 2013: ICT facts and figures. http://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2013.pdf. Accessed 15 May 2013

ISO (2006a) ISO 14040. Environmental Management–Life cycle Assessment–Principles and framework

ISO (2006b) ISO 14044. Environmental Management–Life cycle Assessment–Requirements and Guidelines

Joshi S (1999) Product environmental life-cycle assessment using input–output techniques. J Ind Ecol 3(2–3):95–120

Laurent A, Olsen SI, Hauschild MZ (2012) Limitations of carbon footprint as indicator of environmental sustainability. Environ Sci Technol 46:4100–4108

Lave LB, Cobras-Flores E, Hendrickson C, McMichael F (1995) Using input–output analysis to estimate economy wide discharges. Environ Sci Technol 29:420–426

Lenzen M (2000) Errors in conventional and input–output-based life-cycle inventories. J Ind Ecol 4:127–148

Lindfors L-G, Christiansen K, Hoffman L, Virtanen Y, Juntilla V, Hanssen OJ, Rönning A, Ekvall T, Finnveden G (1995) Nordic guidelines on life-cycle assessment. Nord 1995:20. Nordic Council of Ministers, Copenhagen

Majeau-Bettez G, Strömman A, Hertwich E (2011) Evaluation of process-and input-output-based life cycle inventory data with regard to truncation and aggregation errors. Environ Sci Technol 45: 10170–10177

Malmodin J, Moberg Å, Lundén D, Finnveden G, Lövehagen N (2010) Greenhouse gas emissions and operational electricity use in the ICT and entertainment and media sectors. J Ind Ecol 14:770–790

Moberg Å, Johansson M, Finnveden G, Jonsson A (2010) Printed and tablet e-paper newspaper from an environmental perspective—a screening life cycle assessment. Environ Impact Assess Rev 30: 177–191

Park P-J, Lee K-M, Wimmer W (2006) Development of an environmental assessment method for consumer electronics by combining top-down and bottom-up approaches. Int J Life Cycle Assess 11(4): 254–264

Robinson BH (2009) E-waste: an assessment of global production and environmental impacts. Sci Total Environ 408:183–191

Santavaara I, Paronen N (2013) Nokia's product life cycle assessment over the years, including challenges and key findings. In: Proceedings of the 6th international conference on life cycle management, 39-42, Chalmers University of Technology, Göteborg, Sweden

Singhal P (2005) Integrated product policy pilot on mobile phones stage III final report: evaluation of options to improve the life-cycle environmental performance of mobile phones. Nokia, Espoo

Spielmann M, Bauer C, Dones R, Tuchschmid M (2007) Transport services. Ecoinvent report no. 14. Swiss Centre for Life Cycle Inventories, Dübendorf

Statistics Sweden (2010) Statistics Sweden (2010) Environmental accounts—analysis and simulation. http://www.mirdata.scb.se/MDInfo.aspx. Accessed 10 Nov 2010

Suh S (ed) (2009) Handbook of input output economics in industrial ecology. Springer, Dordrecht

Suh S, Huppes G (2002) Missing inventory estimation tool using extended input-output analysis. Int J Life Cycle Assess 7:134–140

Suh S, Lenzen M, Treloar GJ, Hondo H, Horvath A, Huppes G, Jolliet O, Klann U, Krewitt W, Moriguchi Y, Munksgaard J, Norris G (2004) System boundary selection in life-cycle inventories using hybrid approaches. Environ Sci Technol 38:657–664

Teehan P, Kandlikar M (2012) Sources of variation in life cycle assessments of desktop computers. J Ind Ecol 16:S182–S194

Teehan P, Kandlikar M (2013) Comparing embodied greenhouse gas emissions of modern computing and electronics products. Environ Sci Technol 47:3997–4003

Todd JA, Curran MA (eds) (1999) Streamlined life-cycle assessment: a final report from the SETAC North America Streamlined LCA Workgroup. Society of Environmental Toxicology and Chemistry (SETAC) and SETAC Foundation for Environmental Education

Umair S, Björklund A, Ekener Petersen E (2013) Social life cycle inventory and impact assessment of informal recycling of electronic ICT waste in Pakistan. In: Hilty L, Aebischer E, Andersson G, Lohmann W, Proceedings of the First International Conference on Information and Communication Technologies for Sustainability ETH Zurich, February 14-16, 2013, 52-58. ETH Zurich, University of Zurich and Empa, Swiss Federal Laboratories for Materials Science and Technology

Williams E (2004) Energy intensity of computer manufacturing: hybrid assessment combining process and economic input-output methods. Environ Sci Technol 38(22):6166–6174

Williams E, Babbitt C, Matthews SH, Weber C (2011) Comment on "comparative assessment of life cycle assessment methods used for personal computers. Environ Sci Technol 45(16):7096–7097

Yao MA, Higgs TG, Cullen MJ, Stewart S, Brady TA (2010) Comparative assessment of life cycle assessment methods used for personal computers. Environ Sci Technol 44(19):7335–7346